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22 MAR 1999

The Patent Office

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1. Your reference	**57.0326 GB NP**

2. Patent application number
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2 2 MAR 1999   **9906456.0**

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

Geco-Prakla (UK) Limited

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United Kingdom   6337892061

Patents ADP number *(if you know it)*

If the applicant is a corporate body, give the country/state of its incorporation

United Kingdom

4. Title of the invention

Method and System For Reducing Effects of Sea Surface Ghost Contamination In Seismic Data

5. Name of your agent *(if you have one)*

WANG, William L.

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

c/o Schlumberger Cambridge Research Ltd
High Cross, Madingley Road
Cambridge
CB3 0EL   7626616001

Patents ADP number *(if you know it)*

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Number of earlier application	Date of filing *(day / month / year)*

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Claim(s)	9
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I/We request the grant of a patent on the basis of this application.

Signature   Date

                                               22 March 1999

12. Name and daytime telephone number of
    person to contact in the United Kingdom   WANG, William L.   01223-325439

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Patents Form 1/77

Method and System For Reducing Effects of Sea Surface Ghost Contamination In Seismic Data

FIELD OF THE INVENTION:

5   The present invention relates to the field of reducing the effects of sea-surface ghost reflections in seismic data. In particular, the invention relates an improved de-ghosting method that utilises multi-component marine seismic data recorded in a fluid medium.

10

BACKGROUND OF THE INVENTION:

Figure 1 is a schematic diagram showing reflections between a sea surface (S), sea floor (W) and a target reflector (T). Various events that will be recorded

15   in the seismogram are shown and are labelled according to the series of interfaces they are reflected at. The stars indicate the seismic source and the arrowheads indicate the direction of propagation at the receiver. Events ending with 'S' were last reflected at the rough sea surface and

20   are called receiver ghost events. Down-going sea-surface ghost reflections are an undesirable source of contamination, obscuring the interpretation of the desired up-going reflections from the earth's sub-surface.

Removing the ghost reflections from seismic data

25   is for many experimental configurations equivalent to up/down wavefield separation of the recorded data. In such configurations the down-going part of the wavefield represents the ghost and the up-going wavefield represents the desired signal. Exact filters for up/down separation of

30   multi-component wavefield measurements in Ocean Bottom Cable (OBC) configurations have been derived by Amundsen and

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Ikelle, and are described in U.K. Patent Application Number
9800741.2. An example of such a filter corresponding to de-
ghosting of pressure data at a frequency of 50 Hz for a
seafloor with P-velocity of 2000 m/s, S-velocity of 500 m/s
5   and density of 1800 kg/m3 is shown in Figure 2. At this
frequency, the maximum horizontal wavenumber for P-waves
right below the seafloor is $k=0.157$ m^{-1}, whereas it is
$k=0.628$ m^{-1} for S-waves. Notice the pole and the kink due to
a zero in the filter at these two wavenumbers, making
10   approximations necessary for robust filter implementations.
Figure 3 shows approximations to the filter. These filters
are only good at wavenumbers smaller than the wavenumber
where the pole occurs. Hence, energy with low apparent
velocities (for instance S-waves or Scholte waves at the
15   seafloor) will not be treated properly. Moreover, since
they do not have a complex part, evanescent waves will also
not be treated properly.
        The OBC de-ghosting filters have been shown to
work very well on synthetic data. However, apart from the
20   difficulty with poles and zeros at critical wave numbers,
they also require knowledge about the properties of the
immediate sub-bottom locations as well as
hydrophone/geophone calibration and coupling compensation.
        A normal incidence approximation to the de-
25   ghosting filters for data acquired at the sea floor was
described by Barr, F.J. in U.S. Patent: 4,979,150, issued
1990, entitled 'System for attenuating water-column
reflections', (hereinafter "Barr (1990)"). For all
practical purposes, this was previously described by White,
30   J.E., in a 1965 article entitled 'Seismic waves: radiation,
transmission and attenuation', McGraw-Hill (hereinafter

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"White (1965)"). However, this technique is not effective
when the angle of incidence is away from vertical. Also,
this technique does not completely correct for wide-angle
scattering and the complex reflections from rough sea
5   surfaces.

SUMMARY OF THE INVENTION:
          Rough seas are a source of noise in seismic data.
Aside from the often-observed swell noise, further errors
10   are introduced into the reflection events by ghost
reflection and scattering from the rough sea surface. The
rough sea perturbed ghost events introduce errors that are
significant for time-lapse seismic surveying and the
reliable acquisition of repeatable data for stratigraphic
15   inversion.
          The effect of the rough sea is to perturb the
amplitude and arrival time of the sea surface reflection
ghost and add a scattering coda, or tail, to the ghost
impulse. The impulse response can be calculated by finite
20   difference or Kirchhoff methods (for example) from a
scattering surface which represents statistically typical
rough sea surfaces. For example, a directional form of the
Pierson-Moskowitz spectrum described by Pierson, W.J. and
Moskowitz, L., 1964 'A proposed Spectral Form for Fully
25   Developed Wind Seas Based on the Similarity Theory of S. A.
Kitaigorodskii' J. Geo. Res., 69, 24, 5181-5190,
(hereinafter "Pierson and Moskowitz (1964)"), and
Hasselmann, D. E., Dunckel, M. and Ewing, J.A., 1980
'Directional Wave Spectra Observed During JONSWAP 1973', J.
30   Phys. Oceanography, v10, 1264-1280, (hereinafter "Hasselmann
et al, (1980)"). Both the wind's speed and direction define

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the spectra. The Significant Wave Height ("SWH") is the subjective peak to trough wave amplitude, and is about equal to 4 times the RMS wave height. Different realisations are obtained by multiplying the 2D surface spectrum by Gaussian

5   random numbers.

Figure 4 shows an example of rough sea impulses along a 400m 2D line (e.g. streamer) computed under a 2m SWH 3D rough sea surface. The streamer shape affects the details of the impulses, and in this example the streamer is

10   straight and horizontal. Figure 4 shows, from top to bottom: The ghost wavelet (white trough) arrival time, the ghost wavelet maximum amplitude, a section through the rough sea realisation above the streamer, and the computed rough sea impulses. The black peak is the upward travelling wave,

15   which is unperturbed; the white trough is the sea ghost reflected from the rough sea surface. The latter part of the wavelet at each receiver is the scattering coda from increasingly more distant parts of the surface. Notice that the amplitude and arrival time ghost perturbations change

20   fairly slowly with offset. The arrival time perturbations are governed by the dominant wavelengths in the sea surface, which are 100-200m for 2-4m SWH seas, and the amplitude perturbations are governed by the curvature of the sea surface which has an RMS radius of about 80m and is fairly

25   independent of sea state. The diffraction coda appear as quasi-random noise following the ghost pulse.

The rough sea perturbations cause a partial fill and a shift of the ghost notch in the frequency domain. They also add a small ripple to the spectrum, which amounts to 1-

30   2dB of error for typical sea states. In the post stack

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domain this translates to an error in the signal that is about -20dB for a 2m SWH sea.

Figure 5 shows an example of how such an error can be significant for time-lapse surveys. The panel on the top

5   left shows a post-stack time-migrated synthetic finite difference seismic section. The top middle panel shows the same data but after simulating production in the oil reservoir by shifting the oil water contact by 6m and introducing a 6m partial depletion zone above this. The

10   small difference is just noticeable on the black leg of the reflection to the right of the fault just below 2s two-way travel-time. The panel on the right (top) shows the difference between these two sections multiplied by a factor of 10. This is the ideal seismic response from the time-

15   lapse anomaly.

The left and middle bottom panels show the same seismic sections, but rough sea perturbations for a 2m SWH (as described above) have been added to the raw data before processing. Note that different rough sea effects are added

20   to each model to represent the different seas at the time of acquisition. The difference obtained between the two sections is shown on the bottom right panel (again multiplied by a factor of 10). The errors in the reflector amplitude and phase (caused by the rough sea perturbations)

25   introduce noise of similar amplitude to the true seismic time-lapse response. To a great extent, the true response is masked by these rough sea perturbations. A method for correcting these types of error is clearly important in such a case, and with the increasing requirement for higher

30   quality, low noise-floor data, correction for the rough sea ghost becomes necessary even in modest sea states.

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Thus, it is an object of the present invention to provide a method of de-ghosting which is effective at attenuating noise from substantially all non-horizontal angles of incidence.

5   It is an object of the present invention to provide a method of de-ghosting of seismic measurements made in a fluid which is effective at attenuating the ghost as well as downward propagating noise from substantially all non-horizontal angles of incidence.

10   Also, it is an object of the present invention to provide a method of de-ghosting which is not critically dependent on knowledge about the properties of the surrounding fluid medium as well as hydrophone/geophone calibration and coupling compensation.

15   Also, it is an object of the present invention to provide a method of de-ghosting whose exact implementation is robust and can be implemented efficiently.

         According to the invention, a method is described for sea surface ghost correction through the application of
20   spatial filters to the case of marine seismic data acquired in a fluid medium. Using, for example, either typical towed streamer or vertical cable geometries. Preferably, both pressure and vertical velocity measurements are acquired along the streamer. The invention takes advantage of non-
25   conventional velocity measurements taken along a marine towed streamer, for example. New streamer designs are currently under development and are expected to become commercially available in the near future. For example, the Defence Evaluation and Research Agency (DERA), based in
30   Dorset, U.K., claim to have successfully built such a streamer for high frequency sonar applications.

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According to an alternative embodiment, the
invention is also applicable to seismic data obtained with
configurations of multiple conventional streamers. Here,
the filters make use of vertical pressure gradient

5   measurements, as opposed to velocity measurements.
According to the invention, an estimate of the vertical
pressure gradient can be obtained from over/under twin
streamer data, or more generally from streamer data acquired
by a plurality of streamers where the streamers are

10   spatially deployed in a manner analogous to that described
in U.K Patent Application Number 9820049.6, by Robertsson,
entitled 'Seismic detection apparatus and related method"
filed in 1998 (hereinafter "Robertsson (1998)"). For
example, three streamers can be used, forming a triangular

15   shape cross-section along their length. Vertical pressure
gradient data can also be obtained from pressure gradient
measuring devices.

According to the invention, the filters fully
account for the rough sea perturbed ghost, showing

20   improvement over other techniques based on normal incidence
approximations (see e.g., White (1965)), which have been
applied to data recorded at the sea floor.

Advantageously, the results are not sensitive to
streamer depth, allowing the streamer(s) to be towed at

25   depths below swell noise contamination, hence opening up the
acquisition weather window where shallow towed streamer data
would be unusable. Local streamer accelerations will be
minimised in the deep water flow regime, improving
resolution of the pressure, multi-component velocity and

30   pressure gradient measurements.

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Advantageously, there are no filter poles in the
data window, except for seismic energy propagating
horizontally at the compressional wave speed in water.

Advantageously, the filter is not critically
5   dependent on detailed knowledge of the physical properties
of the surrounding fluid medium.

The filters are simple spatial convolutions, and
with the regular geometry of typical towed streamer
acquisition the filters are efficient to apply in the
10   frequency-wavenumber (FK) domain. The filters can also be
formulated for application in other domains, such as time-
space and intercept time-slowness (τ-p).

According to the invention, a method of reducing
the effects in seismic data of downward propagating
15   reflected and scattered acoustic energy travelling in a
fluid medium is provided. The method advantageously makes
use of two types of data: pressure data, that represents the
pressure in the fluid medium, such as sea water, at a number
of locations; and vertical particle motion data, that
20   represents the vertical particle motion of the acoustic
energy propagating in the fluid medium at a number of
locations within the same spatial area as the pressure data.
The vertical particle motion data can be in various forms,
for example, velocity, pressure gradient, displacement, or
25   acceleration.

The spatial filter is created by calculating a
number of coefficients that are based on the velocity of
sound in the fluid medium and the density of the fluid
medium. The spatial filter is designed so as to be
30   effective at separating up and down propagating acoustic

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energy over substantially the entire range of non-horizontal incidence angles in the fluid medium.

The spatial filter is applied to either the vertical particle motion data or to the pressure data, and
5 then combined with the other data to generate pressure data that has its up and down propagating components separated. The separated data is then processed further and analysed.

BRIEF DESCRIPTION OF THE DRAWINGS:

10 Figure 1 shows examples of simple seismic ray paths for primary events, and ghosts that are last reflected from the rough sea-surface;

Figure 2 shows an exact pressure de-ghosting filter for OBC data for a seafloor with P-velocity of 2000
15 m/s, S-velocity of 500 m/s and density of 1800 kg/m3; the upper panel shows the Real part of exact filter; and the lower panel shows the Imaginary part of exact filter;

Figure 3 shows the Real part of the exact OBC de-ghosting filter (in the solid line) shown in Figure 2, the
20 first order Taylor approximation filter (in the plus line), and the first four fractional expansion approximations filters (in the dash-dotted lines);

Figure 4 illustrates the potential impact of 3D rough sea surface ghost reflection and scattering on
25 consistency of the seismic data waveform;

Figure 5 illustrates the potential impact of the rough sea surface ghost perturbation on time-lapse seismic data quality;

Figure 6 shows exemplary acquisition set-up and
30 streamer configurations according to a preferred embodiment of the invention for towed streamer data acquisition;

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Figure 7 shows an exemplary two-dimensional spatial filter response (ω/k_z) for dx=6m;

Figure 8 is a flow chart illustrating some of the steps of the de-ghosting method for the combination of
5   pressure and vertical velocity data to achieve separated pressure data, according to a preferred embodiment of the invention;

Figure 9 schematically illustrates an example of a data processor that can be used to carry out preferred
10   embodiments of the invention;

Figure 10 shows an example of a shot record computed below a 4m significant wave height (SWH) rough sea surface, the left panel shows pressure, and the right panel shows vertical velocity scaled by water density and the
15   compressional wave speed in water;

Figure 11 illustrates de-ghosting results of the shot record in Figure 10, the left panel shows results using the vertical incidence approximation, and the right panel illustrates the exact solution;

20   Figure 12 illustrates an example of de-ghosting results in detail for a single trace at 330m offset corresponding to an arrival angle of about 37 degrees, the upper panel shows the vertical incidence approximation, and the lower panel shows the Exact solution; and
25   Figure 13 illustrates two examples of multi-component streamer design.

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DETAILED DESCRIPTION OF THE INVENTION:

Equation (1) gives the frequency domain expression
the filter relating the up-going pressure field, $p^u(x)$, to

5   the total pressure, $p(x)$, and vertical particle velocity,
$v_z(x)$.

$$p^u(x)=0.5 \left[p(x) + \frac{\rho \omega}{k_z} * v_z(x) \right] \qquad (1)$$

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where k_z is the vertical wavenumber for
compressional waves in the water, ρ is the density of water
and * denotes spatial convolution.

The vertical wavenumber is calculated from $k_z^2=k^2-$

15   k_x^2 for two-dimensional survey geometries, or $k_z^2=k^2-k_x^2-k_y^2$
for three-dimensional survey geometries, with $k^2=\omega^2/c^2$, where
c is the compressional wave speed in the water and k_x is the
horizontal wavenumber for compressional waves in the water.
The regular sampling of typical towed streamer data allows k_z

20   to be calculated efficiently in the FK domain. Figure 7
shows an example of the filter response, ω/k_z for dx=6m (the
filter is normalised for the display to an arbitrary value).
Infinite gain poles occur when k_z is zero. This corresponds
to energy propagating horizontally (at the compressional

25   wave speed in water). For towed streamer data, there is
little signal energy with this apparent velocity, any noise
present in the data with this apparent velocity needs to be
filtered out prior to the filter application, or, the filter
needs to be tapered at the poles prior to application to

30   avoid amplification of the noise.

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The traditional filter (White (1965), Barr, (1990)) is equation (2).

$$p^u = 0.5 \left[p + \rho c\ v_z \right] \qquad (2)$$

5   By comparison to equation (1), we see that this is a normal incidence approximation, which occurs when k_x is zero. This is implemented as a simple scaling of the vertical velocity trace followed by its addition to the pressure trace.

10   Equation (1) can also be formulated in terms of the vertical pressure gradient $(dp(x)/dz)$. The vertical pressure gradient is proportional to the vertical acceleration:

15    $$dp(x)/dz = \rho\ dv_z(x)/dt \qquad (3)$$

Integrating in the frequency domain through division of $i\omega$, and substituting in equation (1) gives:

20    $$p^u(x) = 0.5 \left[p(x) + \frac{1}{ik_z} * dp(x)/dz \right] \qquad (4)$$

Figure 6 shows exemplary acquisition set-up and
25 streamer configurations according to a preferred embodiment of the invention for towed streamer data acquisition. According to the invention, the down-going rough sea receiver ghost is removed from the data. Examples acquisition set-ups and streamer configurations include:
30 Multi-component streamer with coincident hydrophones and 3C geophones as show in Figure 6(a), coincident hydrophones and

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pressure gradient measuring devices as shown in Figure 6(b),
and dual/multiple streamers as shown in Figure 6(c).

Figure 8 is a flow chart illustrating some of the
steps of the de-ghosting method for the combination of
5   pressure and vertical velocity data to achieve separated
pressure data, according to a preferred embodiment of the
invention. In step 202, spatial filter coefficients are
calculated. The coefficients are preferably dependent on
the characteristics of the acquisition parameters 203 (such
10 as the temporal sample interval of the pressure and particle
motion data, the spatial separation of the vertical particle
motion measuring devices, and the spatial aperture of the
filter), the density of the fluid medium 206, and the speed
of the compressional wave in the fluid medium (or velocity
15 of sound) 204. Vertical particle motion data 208 and
pressure data 212 are received, typically stored as time
domain traces on a magnetic tape or disk. In step 210, the
vertical particle motion data 208 are convolved in with the
spatial filter to yield filtered vertical particle motion
20 data. In step 214 the filtered vertical particle motion
data are added to pressure data 212 to give the downward
propagating component of the separated pressure data.
Alternatively, in step 216 the filtered vertical particle
motion data are subtracted from pressure data 212 to give
25 the upward propagating component of the separated pressure
data. Finally, in step 218 the upward component is further
processes and analysed.

The processing described herein is preferably
performed on a data processor configured to process large
30 amounts of data. For example, Figure 9 illustrates one
possible configuration for such a data processor. The data

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processor typically consists of one or more central
processing units 350, main memory 352, communications or I/O
modules 354, graphics devices 356, a floating point
accelerator 358, and mass storage devices such as tapes and
5   discs 360.

Figure 10 shows a shot record example, computed
under a 4m Significant Wave Height (SWH) sea and using the
finite-difference method described by Robertsson, J.O.A.,
Blanch, J.O. and Symes, W.W., 1994 'Viscoelastic finite-
10 difference modelling' Geophysics, 59, 1444-1456 (hereinafter
"Robertsson et al. (1994)") and Robertsson, J.O.A., 1996 'A
Numerical Free-Surface Condition for Elastic/Viscoelastic
Finite-difference modelling in the Presence of Topography',
Geophysics, 61, 6, 1921-1934 (hereinafter "Robertsson
15 (1996)"). The streamer depth in this example is 60m. The
left panel shows the pressure response and the right panel
shows the vertical velocity response scaled by the water
density and the compressional wave speed in water. A point
source 50Hz Ricker wavelet was used and the streamer depth
20 was 60m in this example. The choice of streamer depth allows
a clear separation of the downward travelling ghost from the
upward travelling reflection energy for visual clarity of
the de-ghosting results. The trace spacing on the plot is
24m. A single reflection and its associated ghost are shown,
25 along with the direct wave travelling in the water layer.
Perturbations in the ghost wavelet and scattering noise from
the rough sea surface are evident.

Figure 11 shows the results of de-ghosting the
shot record shown in Figure 10. The left panel shows the
30 result using the normal incidence approximation and the
right panel shows the result using the exact solution. The

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exact solution shows a consistent response over all offsets, whereas the normal incidence approximation starts to break down at incident angles greater than about 20 degrees, and shows a poorer result at the near offsets. Note that the

5   direct wave is not amplified by the exact filter application even though the poles of the filter lie close to its apparent velocity. The exact filter is tapered before application such that it is has near unity response for frequencies and wavenumbers corresponding to apparent

10   velocities of 1500m/s and greater. The weak event just below the signal reflection is a reflection from the side absorbing boundary of the model. It is upward travelling and hence untouched by the filter.

        Figure 12 shows details of the de-ghosted results

15   for a single trace from Figure 11. The trace offset is 330m corresponding to a 37 degree incidence angle. The upper panel shows the normal incidence approximation, and the lower panel shows the exact solution. Not only does the exact solution provide a superior result in terms of the de-

20   ghosting, but also in terms of amplitude preservation of the signal reflection - the upper panel shows loss of signal amplitude after the de-ghosting.

        The filters described herein are applicable to, for example, measurements of both pressure and vertical

25   velocity along the streamer. Currently, however, only pressure measurements are commercially available. Therefore, engineering of streamer sections that are capable of commercially measuring vertical velocity is preferred in order to implement the filters.

30   Figure 13 illustrates two possible examples of multi-component streamer design. Figure 13(a) shows a

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coincident pressure and single 3-component geophone. In
this design, the 3-component geophone is perfectly decoupled
from the streamer. Figure 13(b) shows a coincident pressure
and twin 3-component geophones. In this design, one of the
5 3-component geophones is decoupled from the streamer, the
other is coupled to the streamer; measurements from both are
combined to remove streamer motion from the data.

In an alternative formulation, the filters make
use of vertical pressure gradient measurements. An estimate
10 of vertical pressure gradient can be obtained from
over/under twin streamers and multiple streamers deployed in
configurations analogous to that described in Robertsson
(1998), allowing the filters to be directly applied to such
data. However, for the results to remain sufficiently
15 accurate, the streamers should not be vertically separated
by more than 2m for seismic frequencies below approximately
80Hz.

An important advantage of multiple streamer
configurations is that their relative locations are less
20 crucial than for over/under twin streamer geometries, where
the two streamers are preferably directly above one another.

The filters described here are applied in 2D
(along the streamer) to data modelled in 2D. The application
to towed streamer configurations naturally lends itself to
25 this implementation, the cross-line (streamer) sampling of
the wavefield being usually insufficient for a full 3D
implementation. Application of these filters to real data
(with ghost reflections from 3D sea surfaces) will give rise
to residual errors caused by scattering of the wavefield
30 from the cross-line direction. This error increases with

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frequency though is less than 0.5dB in amplitude and 3.6° in phase for frequencies up to 150Hz, for a 4m SWH sea. These small residual noise levels are acceptable when time-lapse seismic surveys are to be conducted.

5   Adequate spatial sampling of the wavefield is highly preferred for the successful application of the de-ghosting filters. For typical towed streamer marine data, a spatial sampling interval of 12m is adequate for all incidence angles. However, to accurately spatially sample

10   all frequencies up to 125Hz (for all incidence angles), a spatial sampling interval of 6.25 meters is preferred. The filters can be applied equally to both group formed or point receiver data.

      Invoking the principle of reciprocity, the filters

15   can be applied in the common receiver domain to remove the downward travelling source ghost. Reciprocity simply means that the locations of source and receiver pairs can be interchanged, (the ray path remaining the same) without altering the seismic response. Figure 1 can also be used to

20   define the source ghost if the stars are now regarded as receivers and the direction of the arrows is reversed, with the source now being located at the arrow. This application is particularly relevant for data acquired using vertical cables, which may be tethered, for example, to the sea

25   floor, or suspended from buoys.

      While preferred embodiments of the invention have been described, the descriptions and figures are merely illustrative and are not intended to limit the present invention.

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CLAIMS

What is claimed is:

5   1.   A method of reducing the effects in seismic
data of downward propagating reflected and scattered
acoustic energy travelling in a fluid medium comprising the
steps of:
            receiving pressure data representing at least
10   the pressure in the fluid medium at a first location
and a second location, the first location being in
close proximity to the second location;
            receiving vertical particle motion data
representing at least the vertical particle motion of
15   acoustic energy propagating in the fluid medium at a
third location and a fourth location, the third
location being in close proximity to the fourth
location, and the first, second, third and fourth
locations being within a spatial area;
20   calculating a plurality of spatial filter
coefficients based in part on the velocity of sound in
the fluid medium, the density of the fluid medium and a
plurality of acquisition parameters, thereby creating a
spatial filter which is designed so as to be effective
25   at separating up and down propagating acoustic energy
over a range of non-vertical incidence angles in the
fluid medium;
            applying the spatial filter to the vertical
particle motion data to generate filtered particle
30   motion data;

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combining the filtered particle motion data
with the pressure data to generate separated pressure
data, the separated pressure data having up and down
propagating components separated; and

5   analysing at least part of the up propagating
component of the separated pressure data.

2.   The method of claim 1 wherein the acquisition
parameters include the temporal sampling interval, the
10   spatial sampling interval, and the number of independent
locations at which the pressure and vertical particle motion
data are measured.

3.   The method of claim 1 wherein the vertical
15   particle motion data is measured using one or more multi-
component streamers.

4.   The method of claim 1 wherein the vertical
particle motion of the acoustic energy represented in said
20   vertical particle motion data is the particle velocity of
the acoustic energy.

5.   The method of claim 1 wherein the vertical
particle motion of the acoustic energy represented in said
25   vertical particle motion data is the vertical pressure
gradient of the acoustic energy.

6.   The method of claim 5 wherein the pressure
gradient is measured using at least two parallel streamer
30   cables in close proximity and vertically offset from one
another.

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7.   The method of claim 1 wherein the vertical particle motion of the acoustic energy represented in said vertical particle motion data is the vertical displacement
5   of the acoustic energy.

8.   The method of claim 1 wherein the vertical particle motion of the acoustic energy represented in said vertical particle motion data is the vertical acceleration
10   of the acoustic energy.

9.   The method of claim 1 wherein the distance between the first location and the second location and the distance between the third location and the fourth location
15   is less than the Nyquist spatial sampling criterion.

10.   The method of claim 9 wherein the spatial area is substantially a portion of a line, and the range of non-vertical incidence angles includes substantially all
20   non-horizontal incidence angles within a vertical plane that passes through the portion of line.

11.   The method of claim 9 wherein the spatial area is a portion of a substantially planar region, and the
25   range of non-vertical incidence angles include substantially all non-horizontal incidence angles.

12.   A method of reducing the effects in seismic
30   data of downward propagating reflected and scattered

20

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acoustic energy travelling in a fluid medium comprising the steps of:

receiving pressure data representing at least the pressure in the fluid medium at a first location and a second location, the first location being in close proximity to the second location;

receiving vertical particle motion data representing at least the vertical particle motion of acoustic energy propagating in the fluid medium at a third location and a fourth location, the third location being in close proximity to the fourth location, and the first, second, third and fourth locations being within a spatial area;

calculating a plurality of spatial filter coefficients based in part on the velocity of sound in the fluid medium and the density of the fluid medium, thereby creating a spatial filter which is designed so as to be effective at separating up and down propagating acoustic energy over a range of non-horizontal incidence angles in the fluid medium;

applying the spatial filter to the pressure data to generate filtered pressure data;

combining the filtered pressure data with the vertical particle motion data to generate separated pressure data, the separated pressure data having up and down propagating components separated; and

analysing at least part of the up propagating component of the separated pressure data.

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13.   The method of claim 12 wherein the distance
between the first location and the second location and the
distance between the third location and the fourth location
is less than the Nyquist spatial sampling criterion.

5

14.   The method of claim 12 wherein the vertical
particle motion data is measured using one or more multi-
component streamers.

10   15.   The method of claim 12 wherein the vertical
particle motion of the acoustic energy represented in said
vertical particle motion data is the particle velocity of
the acoustic energy.

15   16.   The method of claim 12 wherein the vertical
particle motion of the acoustic energy represented in said
vertical particle motion data is the vertical pressure
gradient of the acoustic energy.

20   17.   The method of claim 16 wherein the pressure
gradient is measured using at least two parallel streamer
cables in close proximity and vertically offset from one
another.

25   18.   A method of reducing the effects in seismic
data of downward propagating reflected and scattered
acoustic energy travelling in a fluid medium comprising the
steps of:
               receiving pressure data representing at least
30   variations in pressure in the fluid medium at a first
location, the variations caused in part by a first

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source and a second source, the first source and the
second source being within a spatial area;

receiving vertical particle motion data
representing at least the vertical particle motion of
acoustic energy propagating in the fluid medium at a
second location, the acoustic energy being caused in
part by a first source and a second source;

calculating a plurality of spatial filter
coefficients based in part on the velocity of sound in
the fluid medium and the density of the fluid medium,
thereby creating a spatial filter which is designed so
as to be effective at separating up and down
propagating acoustic energy from the first source and
second source over a range of non-horizontal incidence
angles in the fluid medium;

applying the spatial filter to the vertical
particle motion data to generate filtered particle
motion data;

combining the filtered particle motion data
with the pressure data to generate separated pressure
data, the separated pressure data having up and down
propagating components separated; and

analysing at least part of the up propagating
component of the separated pressure data.

19. The method of claim 18 wherein the distance
between the first location and the second location and the
distance between the third location and the fourth location
is less than the Nyquist spatial sampling criterion.

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20.   The method of claim 18 wherein the vertical
particle motion data is measured using one or more multi-
component streamers.

5   21.   The method of claim 18 wherein the vertical
particle motion of the acoustic energy represented in said
vertical particle motion data is the particle velocity of
the acoustic energy.

10   22.   The method of claim 18 wherein the vertical
particle motion of the acoustic energy represented in said
vertical particle motion data is the vertical pressure
gradient of the acoustic energy.

15   23.   The method of claim 22 wherein the pressure
gradient is measured using at least two parallel streamer
cables in close proximity and vertically offset from one
another.

20   24.   A computer-readable medium which can be used
for directing an apparatus to reduce the effects in seismic
data of downward propagating reflected and scattered
acoustic energy travelling in a fluid medium comprising:
                 means for retrieving pressure data
25   representing at least the pressure in the fluid medium
         at a first location and a second location, the first
         location being in close proximity to the second
         location;
                 means for retrieving vertical particle motion
30   data representing at least the vertical particle motion
         of acoustic energy propagating in the fluid medium at a

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third location and a fourth location, the third location being in close proximity to the fourth location, and the first, second, third and fourth locations being within a spatial area;

5   means for calculating a plurality of spatial filter coefficients based in part on the velocity of sound in the fluid medium, the density of the fluid medium and a plurality of acquisition parameters, thereby creating a spatial filter which is designed so

10   as to be effective at separating up and down propagating acoustic energy over a range of non-vertical incidence angles in the fluid medium;

          means for applying the spatial filter to the vertical particle motion data to generate filtered

15   particle motion data;

          means for combining the filtered particle motion data with the pressure data to generate separated pressure data, the separated pressure data having up and down propagating components separated;

20   and

          means for analysing at least part of the up propagating component of the separated pressure data.

          25. The computer-readable medium of claim 24

25 wherein the distance between the first location and the second location and the distance between the third location and the fourth location is less than the Nyquist spatial sampling criterion.

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26.   The computer-readable medium of claim 24
wherein the vertical particle motion data is measured using
one or more multi-component streamers.

5   27.   The computer-readable medium of claim 24
wherein the vertical particle motion of the acoustic energy
represented in said vertical particle motion data is the
particle velocity of the acoustic energy.

10   28.   The computer-readable medium of claim 24
wherein the vertical particle motion of the acoustic energy
represented in said vertical particle motion data is the
vertical pressure gradient of the acoustic energy.

15   29.   The computer-readable medium of claim 28
wherein the pressure gradient is measured using at least two
parallel streamer cables in close proximity and vertically
offset from one another.

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ABSTRACT

An improved de-ghosting method and system that
utilises multi-component marine seismic data recorded in a
5   fluid medium is disclosed. The disclosed method makes use
of two types of data: pressure data, that represents the
pressure in the fluid medium, such as sea water, at a number
of locations; and vertical particle motion data, that
represents the vertical particle motion of the acoustic
10   energy propagating in the fluid medium at a number of
locations within the same spatial area as the pressure data.
The vertical particle motion data can be in various forms,
for example, velocity, pressure gradient, displacement, or
acceleration. A spatial filter is designed so as to be
15   effective at separating up and down propagating acoustic
energy over substantially the entire range of non-horizontal
incidence angles in the fluid medium. The spatial filter is
applied to either the vertical particle motion data or to
the pressure data, and then combined with the other data to
20   generate pressure data that has its up and down propagating
components separated.
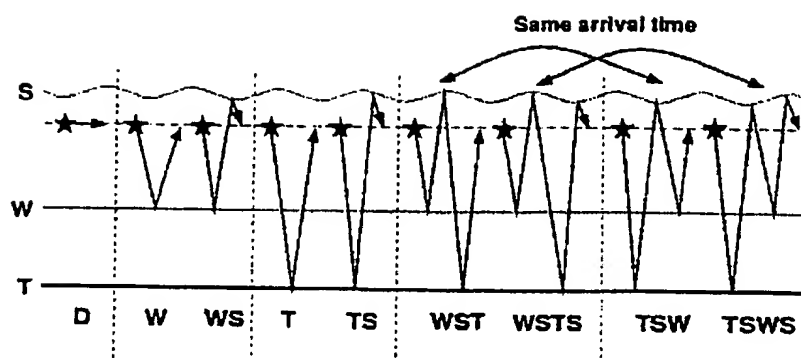
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Figure 1

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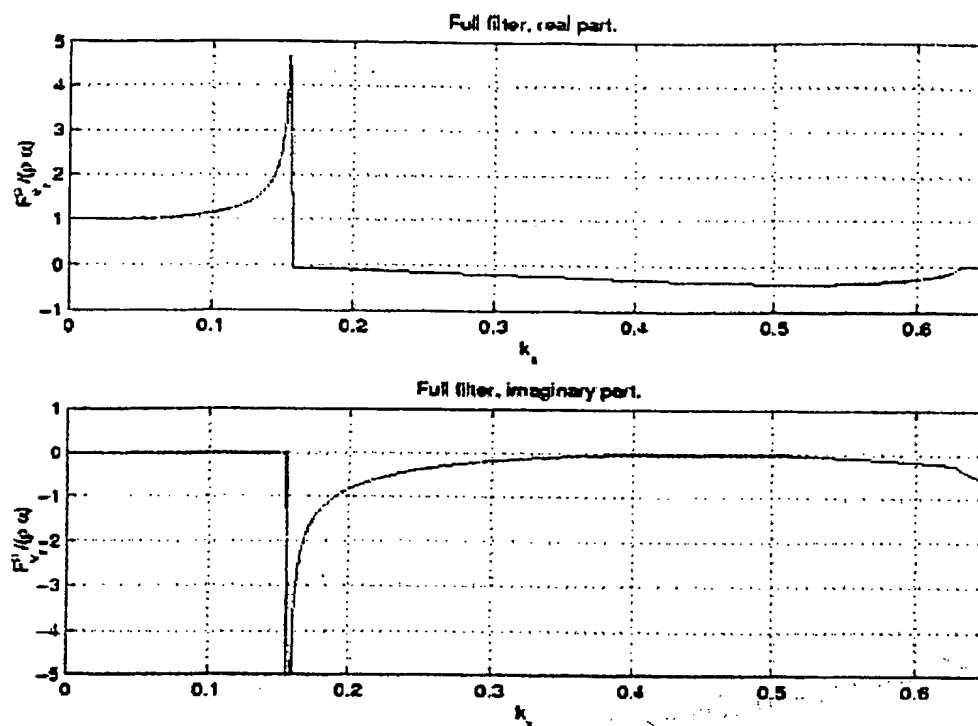
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5   **Figure 2**
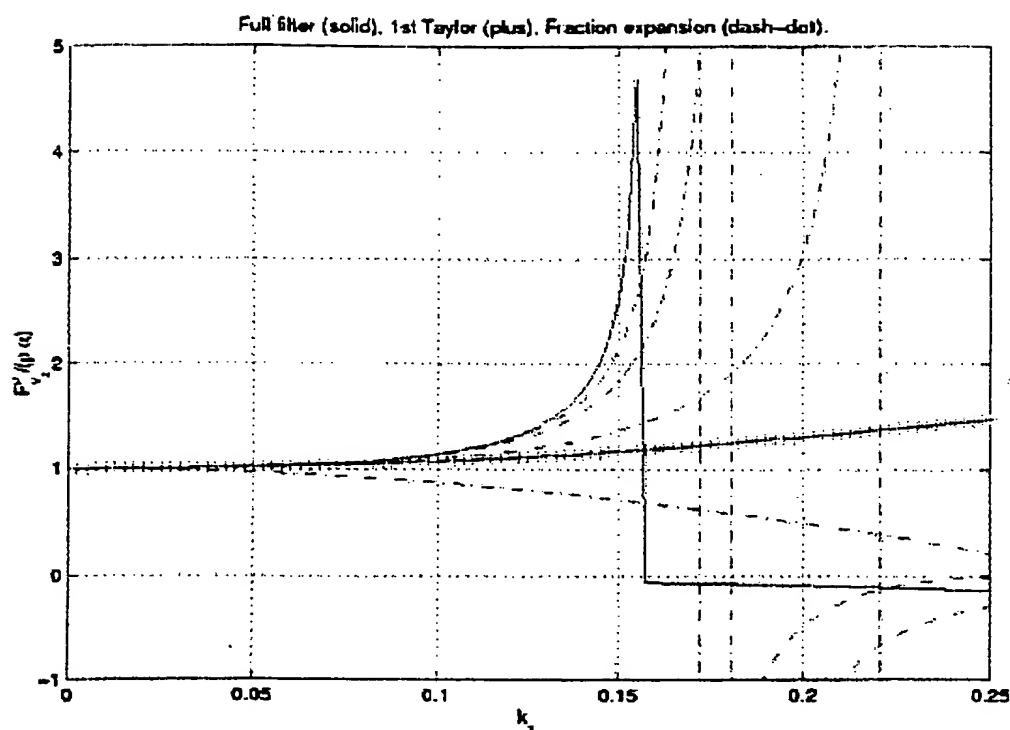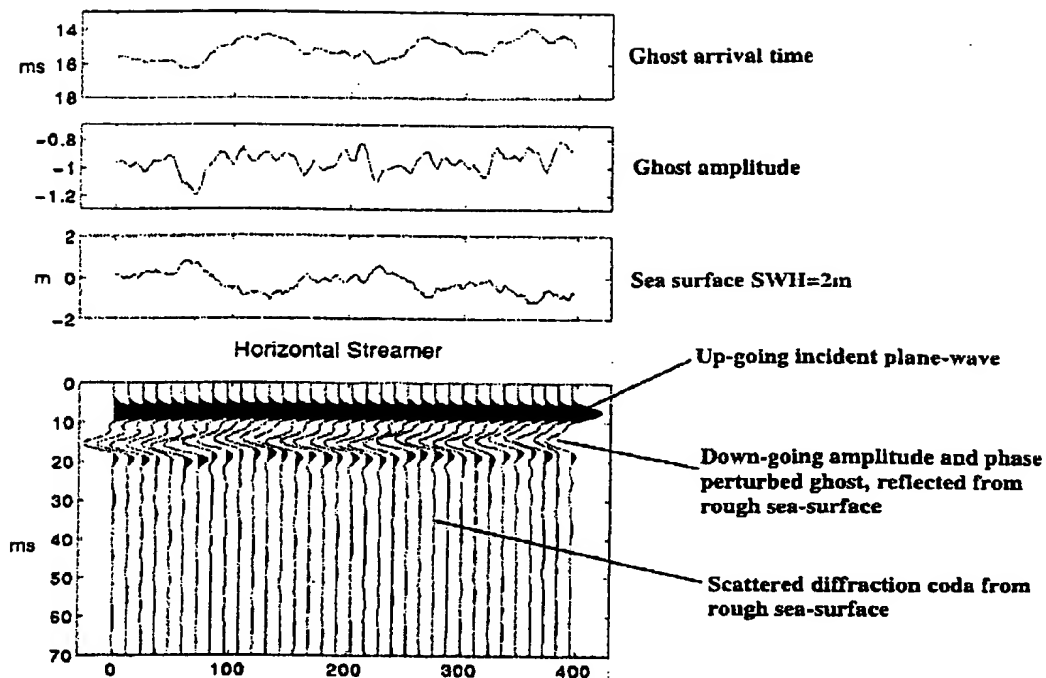
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Figure 3

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Figure 4

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Figure 5

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Seismic vessel

Seismic source

Sea surface

Down-going receiver ghost

Streamer depth e.g., 60 m

Seismic streamer

Seismic energy

Up-going reflection

Transmitted signal

Sea-floor

(a) Multi-component Streamer
Sea surface

P v_x, v_y, v_z

e.g., < 12 m

(b) Multi-component Streamer
Sea surface

P dP/dz

e.g., < 12 m

(c) Dual/Triple Streamer
Sea surface

P

Streamer separation e.g., < 2 m

e.g., < 12 m

Side view:
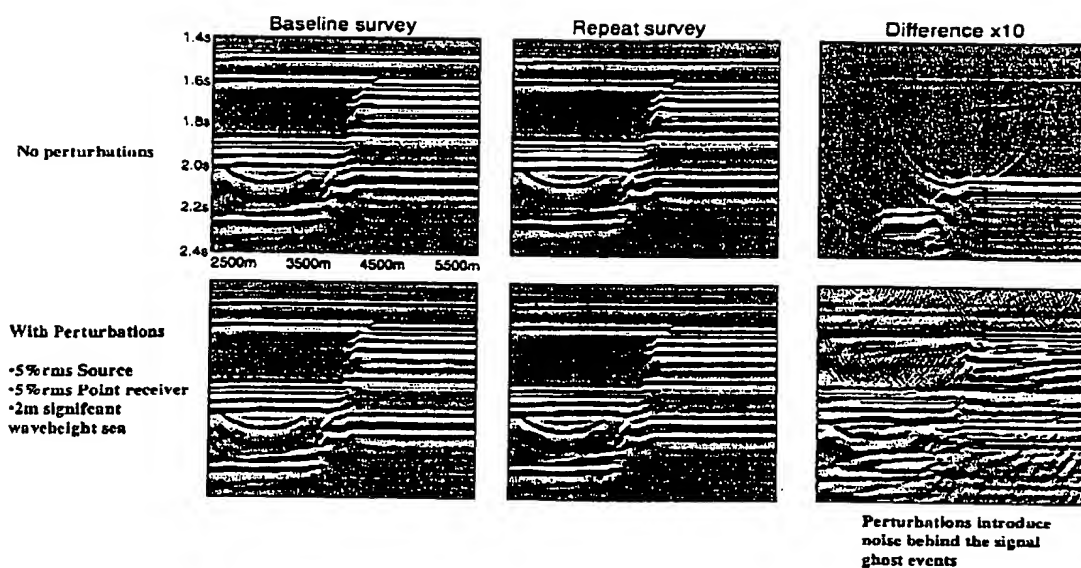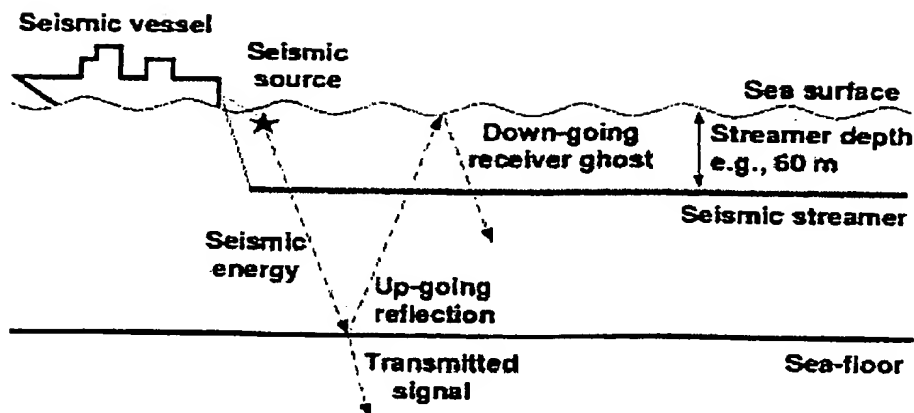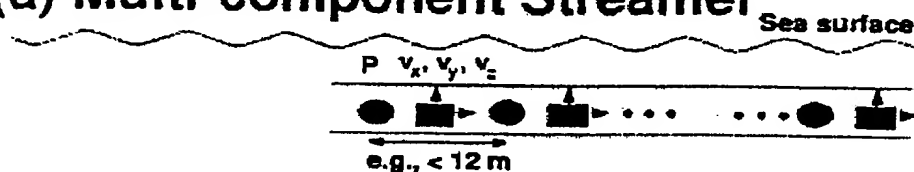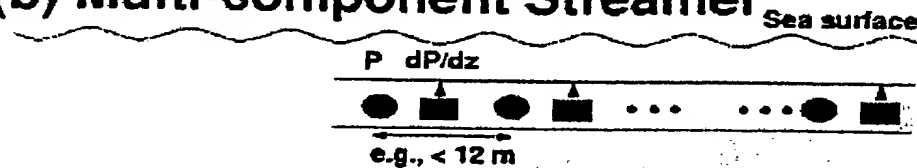
Dual streamer

Triple streamer

Figure 6

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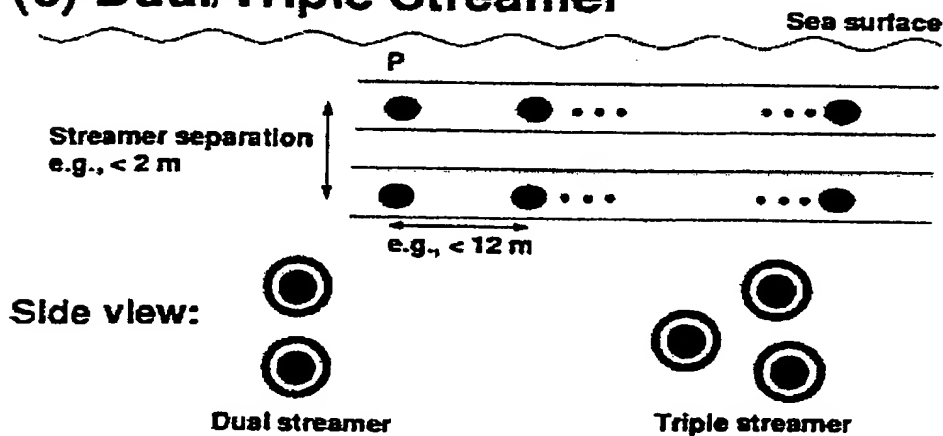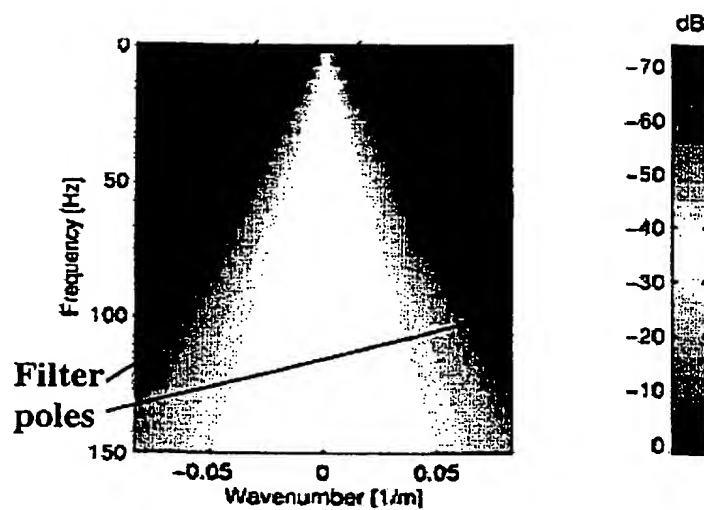
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Figure 7

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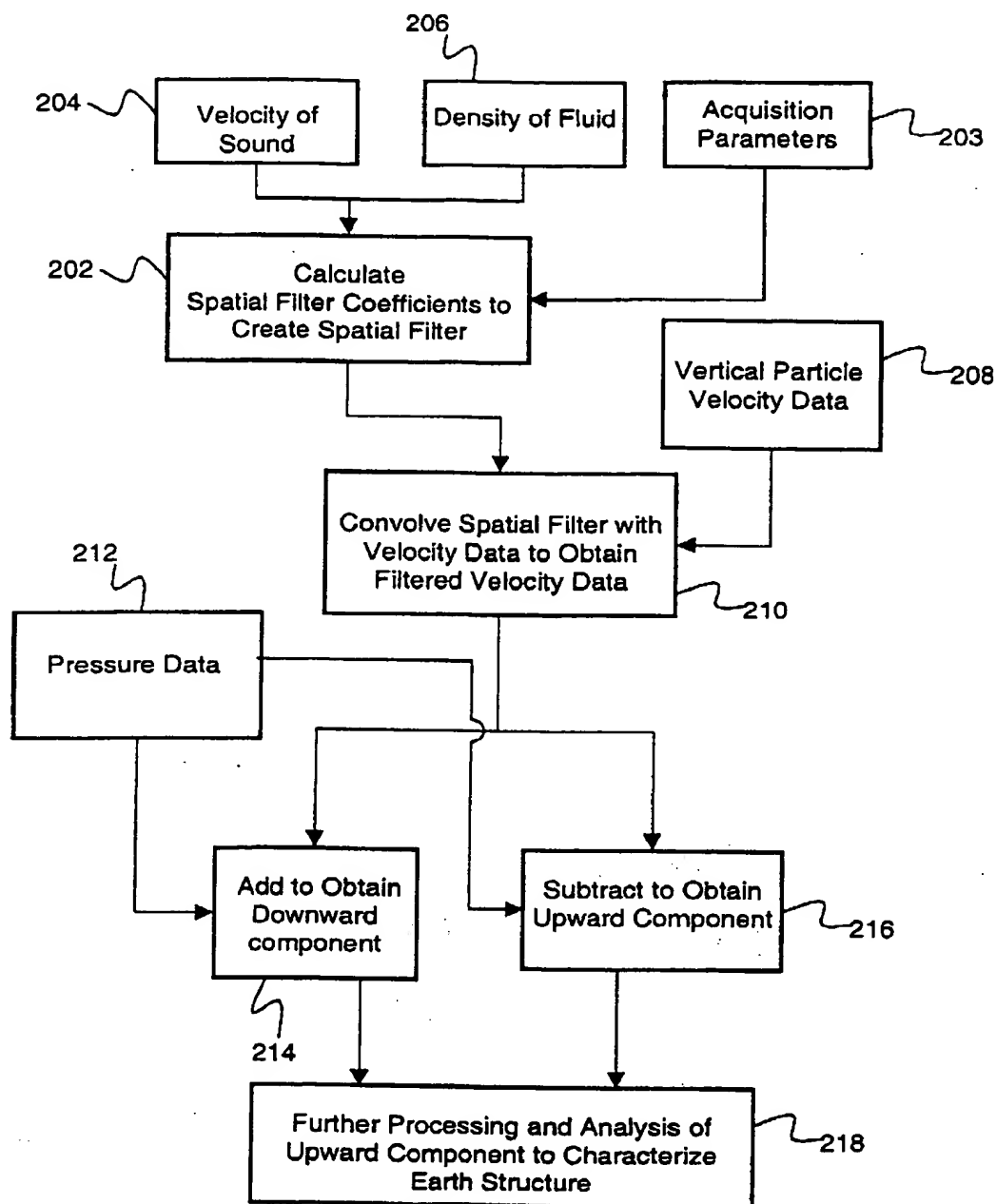
Figure 8

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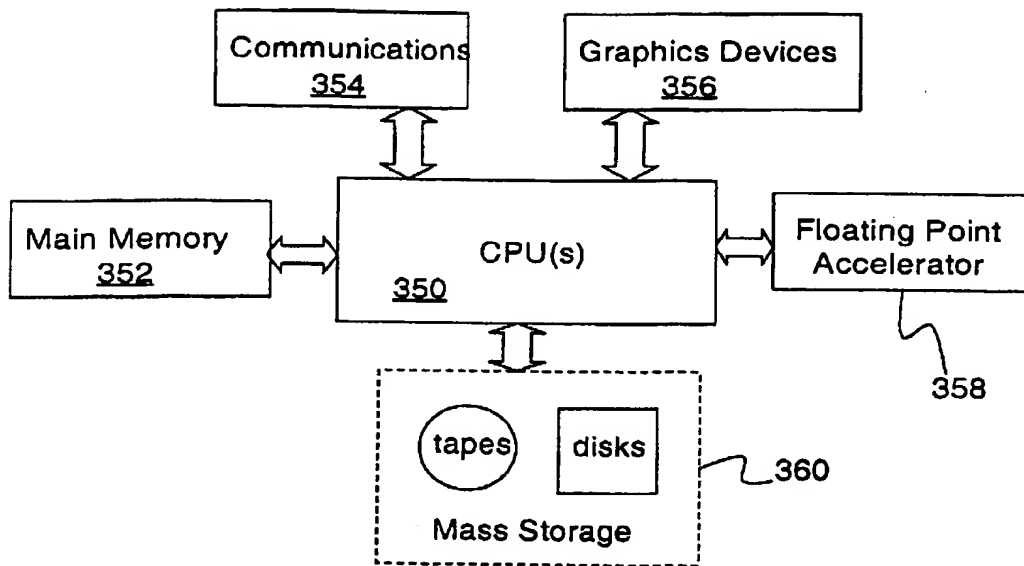
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Figure 9
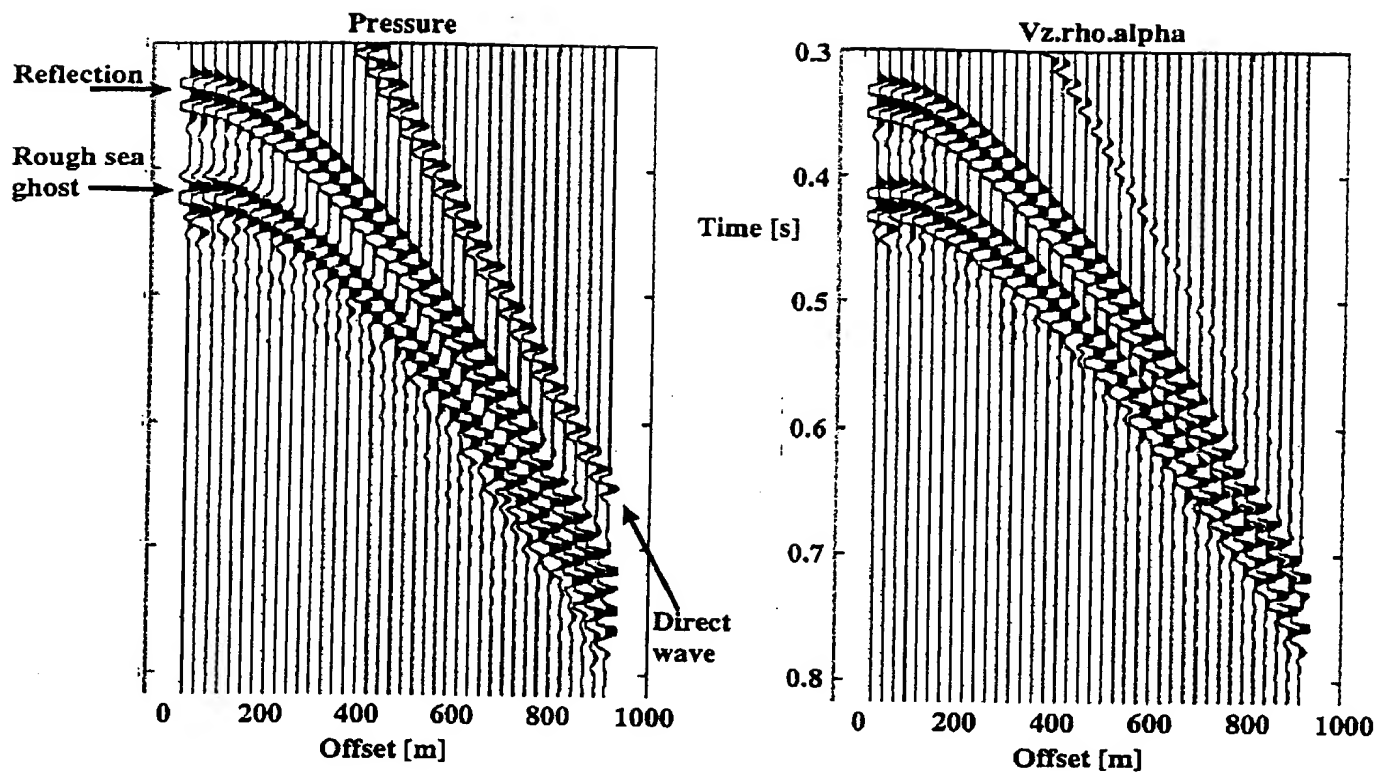
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Figure 10

Figure 11

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Offset =330m Angle -37degrees
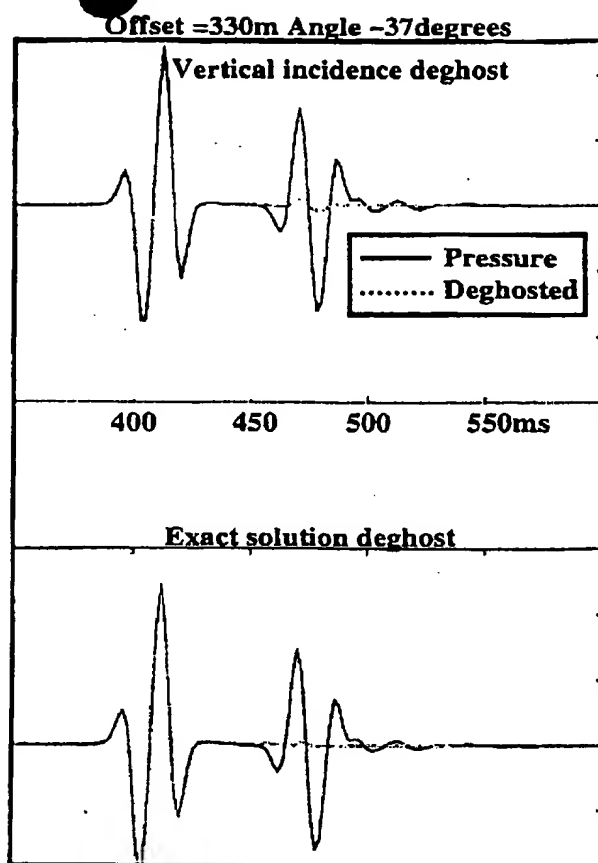
Figure 12.

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a) 4C recording

b) 7C recording

hydrophone   3C geophone - decoupled from streamer

hydrophone   3C geophone - decoupled from streamer   3C geophone - coupled to streamer

streamer skin
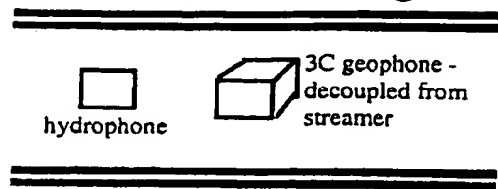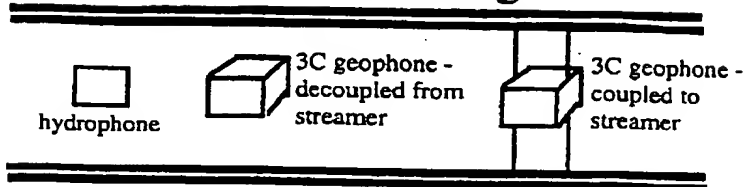
Figure 13

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